The Application of Frequency Hopping CDMA for Future Universal Personal Communications Systems

S.C. Swales, D.J. Purle, T. Busby & M.A. Beach.

Centre for Communications Research, Faculty of Engineering, University of Bristol, Bristol, BS8 1TR, U.K.

Abstract- **The future of mobile telephony is moving towards a universal standard to replace the mixture of technologies that exist in the market place today. In North America, Personal Communications Systems (PCS) have become synonymous with this goal and candidates for the air interface include both CDMA and TDMA. CDMA technology has been dominated by a technique exploiting direct sequence (DS) spread spectrum. An alternative approach employs frequency hopping (FH) spread spectrum, and recent work has shown that the claimed advantages of DS also apply to FH. In this contribution, these claims are investigated and an alternative FH-CDMA architecture proposed to rival current DS-CDMA systems.**

I. INTRODUCTION

The aim of a third generation Personal Communications System (PCS) is to bring together the various forms of wireless networks available today with a single unified standard offering mobile access to a wide range of services. Current proposals are the CCIR global standard, the Future Public Land Mobile Telecommunications System (FPLMTS), and the European Universal Mobile Telecommunications System (UMTS) [1].

The requirements for these systems far exceed those of current generation wireless technology, and can only be satisfied by employing a very flexible air interface [2]. Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) are the currently favoured candidates, with extensive research activities currently underway worldwide to evaluate their suitability, e.g. the RACE initiative in Europe [3]. If either of these techniques is to be universally accepted as the air interface to take wireless communications into the 21st Century, then it will have to meet a number of stringent criteria.

The application of CDMA technology for mobile communications has been the focus of extensive research recently, and the proposed architectures have been the subject of intense scrutiny and detailed comparisons with existing technology. From the wealth of recent published material [4-7], the emerging consensus is clear; CDMA is an attractive candidate for PCS.

The alternative spreading technology to direct sequence is frequency hopping (FH) although, in comparison, this has received relatively little interest recently. The reasons for this are unclear, although early FH proposals did consider only fast frequency hopping [8,9], and with hop rates in excess of 100 khops/sec, the technological challenges are great. Recent FH proposals, however, consider much slower hopping rates ($\leq$ 500 hops/sec), making FH a more realistic prospect [10,11].

Fast frequency hopping (FFH) means that each transmission symbol is transmitted using multiple frequencies, and has the advantage of frequency diversity. With slow hopping, (SFH) multiple symbols are transmitted using the same frequency, and although the frequency diversity advantage is reduced, there are some additional benefits. Firstly, practical hopping RF synthesisers can be realised, as well as relaxing the requirements for the associated acquisition and tracking subsystems. Also, slow hopping offers the potential for synchronous operation within a cell, or group of cells. Each user could then be assigned a unique phase offset of the same hopping sequence, ensuring that they never hop onto the same channel at the same time. This is an extremely desirable feature since it effectively removes the intra-cell interference contribution, greatly improving performance. This is in contrast to DS-CDMA, where the relatively high chipping rates ($\geq$ 1Mchips/sec) possibly preclude this type of operation in a cellular environment.

In this paper, a potential FH-CDMA architecture will be described, including a discussion on both the hardware aspects and the modulation and coding. The results of some computer simulations assessing its performance will then be presented.

II. FH ARCHITECTURE

A. Hardware

In any radio communications system the hardware requirements of the handheld terminal are major factors in determining the viability of the system as a commercial success. Cost, power consumption and size, and indeed technological feasibility for new architectures, are the markers against which a design, or potential design, must be judged. This is particularly so for the emerging CDMA techniques which of necessity embody significant degrees of signal processing electronics, and proposed FH-CDMA schemes are no exception to the deployment of high levels of very high technology circuit integration [12].

Many aspects of handset (and overall system) hardware design may be common to any chosen CDMA technique, but the heart of a FH system that sets it apart from the other techniques is the local oscillator frequency hopping synthesizer. The realisation of this crucial element is heavily technology dependent, and different methods of implementation are suggested for each of FFH or SFH; the choice of whether to fast hop or slow hop also strongly influences the complexity of the synchronisation and tracking blocks in the receiver.

Hop rates up to ~1khop/s, corresponding to SFH, can be accommodated by relatively simple, inexpensive, low power single loop frequency synthesizers, as currently used in many types of communications handsets. Present development of very low power fractional-N synthesizer integrated circuits [13,14], which enable fast frequency switching and good close-to-carrier phase noise performance, are set to offer a low risk solution to the implementation of commercial SFH handsets. Hop rates above 1khop/s, and extending into the 100's or 1000's of khop/s range, as required for a UMTS FFH transceiver, are possible with direct digital synthesizer (DDS) techniques although the practical problems of implementation in order to cover the designated hop bandwidths are demanding.

Recent innovations in digital up/downconverters have created new possibilities in producing FFH (and also SFH) transceivers, using DDS based hopped intermediate frequency (IF) local oscillators for combined IF/baseband synchronisation and tracking functions. The cost, size and power consumptions of the new ASIC's are presently excessive for most commercial applications, and the production of FFH hand-portable hardware is seen to be higher risk than for a SFH system using hopped radio frequency carriers. Also, the added complexity and cost of increasing the hop rate may not deliver a corresponding improvement in capacity. Inevitably advances in semiconductor manufacturing, particularly smaller feature sizes and new geometries, will result in compact, inexpensive, low power drain devices being developed. While such developments are as yet a little way in the future, the possible application of dual-mode FH/DS transceivers could be envisaged, given the requisite system and architecture specifications.

B. Modulation & Coding

The most suitable choice of modulation format and channel coding for FH-CDMA is an issue requiring careful study. On the modulation side some general points can be made: the use of a linear modulation format which utilises both the phase and amplitude of the RF carrier to convey message information is advantageous in that the signal bandwidth required is greatly reduced. Also, the use of premodulation (baseband) pulse shaping reduces the spectral occupancy of such linear modulation schemes to a minimum. When considered in the FH-CDMA scenario, the resulting narrow message bandwidth allows more FH channels in a given spreading bandwidth, increasing the processing gain, and hence immunity to interference.

Any frequency hopped modulation scheme must provide resilience to the fading environment. Most important, however, is the ability to operate non-coherently, due to the phase discontinuities at each hop, and with a rapid response receiver, since the dwell time on any given frequency is limited.

The modulation formats considered here are 16 Level Amplitude and Phase Shift Keying (16APSK) [15], and $\pi/4$ Shifted QPSK. Both schemes are operated differentially, to meet the requirements stated above. The performance of both, with Root Raised Cosine Tx-Rx filtering (α=0.6), in 0.01 Normalised Doppler ($f_d T_s$) is shown in Figure 1. These curves are for a single user link, with a hopping rate of 500hops/sec and a basic data rate of 10kbps. Whilst the 16 level modulation is twice as bandwidth efficient, thereby allowing more channels per MHz of frequency allocation, it clearly suffers an E_b/N_o penalty compared to QPSK, and thus would be more sensitive to multi-user interference. There is clearly a trade-off here, which is more fully discussed in section V.

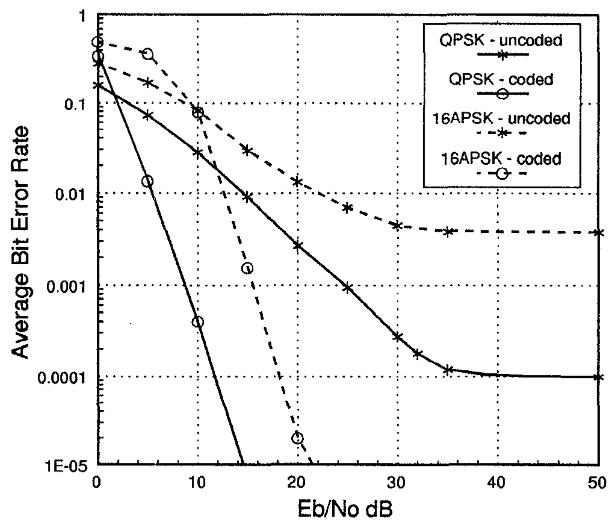

Figure 1: Comparison of 16APSK and QPSK.

FEC Coding and interleaving are an essential requirement for FH-CDMA. In order to avoid a high outage rate arising when data is lost during frequency bin clashes, the user's channel must be made memoryless. Two different forms of coding have been considered to date: 1/2 rate convolutional encoding with a constraint length of 7, and a (15,7) BCH block code. These utilise block interleaving over a user-defined depth, allowing the effects of interference diversity to be investigated. The coded performance of the two modulation schemes over a single user link with half rate convolutional encoding and no interference is also shown in Figure 1.

III. Simulation Tools

A simple schematic of the complete system simulation is shown in figure 2. This involved developing a simulation of the modulation and coding described above operating over a frequency hopped channel. The model developed for 16APSK operation is more fully described by Purle [16].

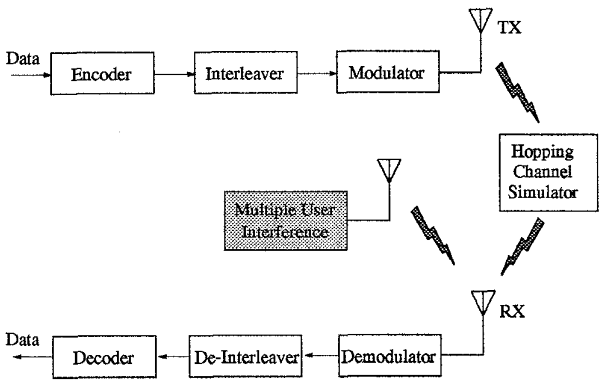

Figure 2: Schematic of FH-CDMA simulation.

In order to simulate the effects of a realistic frequency hopped channel, which negates the need for simulation of a separate frequency hopper, fixed broadband channel model and dehopper, a simplified channel model was developed. This involves generating independently fading data from hop frame to hop frame by adjusting the seeds of a narrowband Rayleigh fading channel. The effect of hopping is simulated by, in effect, taking a different time slice of the fading envelope. The long term statistics of the received signal envelope are no different than that of the unhopped channel, i.e. the cumulative distribution remains virtually unchanged, and this has been confirmed through both simulation and measurement of the FH channel [17].

Recent propagation measurements of the FH channel [17] have also demonstrated that the short term statistics, such as level crossing rate and fade duration, are very much dependent on the hop rate. The results indicate that as the hop rate increases, the level crossing rate also increases with a corresponding reduction in the mean fade duration. The simulated channel model is consistent with the measured data, and enables the effect of different hopping rates to be investigated. This could have crucial implications on the design of any FH system, e.g. it would be advantageous to hop faster due to the reduction in the fade duration. This corresponds to limiting the length of error bursts in deep fades, thereby reducing the requirements upon the demodulating system in terms of the interleaving depth, coding complexity, and fade margin required to allow operation at a specified error rate.

In order to analyse the impact of a fully loaded system, a multiple user scenario must be set up to simulate the effect of the out-of-cell interference. This was achieved by generating a reference interference file for a given network topology, cell loading, propagation environment, voice activity, etc., and adding this directly into the link simulation at run-time as shown in figure 2. The BER performance can then be generated for a given cell loading, although this will only give the average BER for a particular environment and number of users. This is not a suitable measure for the overall network performance, which is normally expressed in terms of an outage probability, i.e. the probability that the link performance falls below a given threshold, e.g. a BER of 10^{-3}. In the following simulations, a single outage is determined over a period of 10^4 information bits, i.e. when more than 10 bits are in error, and this is repeated to generate the overall outage statistics.

IV. Capacity Results

The following describes in full the parameters for the basic FH-CDMA system simulation used in the subsequent analysis. Complete frequency reuse has been assumed within each cell, with synchronous hopping removing all intra-cell interference. Only the uplink is considered at this stage.

Network Topology

- Total number of base-stations: 37 (hexagonal cellular geometry.)

Propagation Environment

- Path loss exponent: 4
- Log-normal shadowing std dev.: 8 dB
- Fast fading: Rayleigh (f_dT_s=0.01)

Miscellaneous

- Power control: Shadowing & path loss
- Power control error (std dev.): 0 dB
- Handover Margin: 0 dB
- Voice activity factor: 0.5
- Cell sectorisation: None
- Antenna diversity: Dual
- Data rate: 10 kbps[1]

The results presented in figure 3 show the outage performance of 16APSK and QPSK at a 1000 hops/s, whilst the results in figure 4 show the performance of QPSK with hop rates of 500 and 1000 hops/s. Half rate convolutional encoding has been employed for each curve with a maximum interleaving delay of 40msec. The coding results in transmission symbol rates of 5kbaud for 16APSK and 10kbaud for QPSK, which can be supported with channel spacings of 8kHz and 16kHz respectively.

Taking a criterion of acceptable system performance as 1% of users being in outage, QPSK at 1000 hops/s offers 24 users/MHz/cell, whereas 16APSK offers only 11 users/MHz/cell. It can be seen in figure 4 that FH operation of QPSK at the slower hopping rate of 500 hops/s reduces the system capacity to 20 users/MHz/cell.

[1] 8kbps speech plus a 2kbps control overhead.

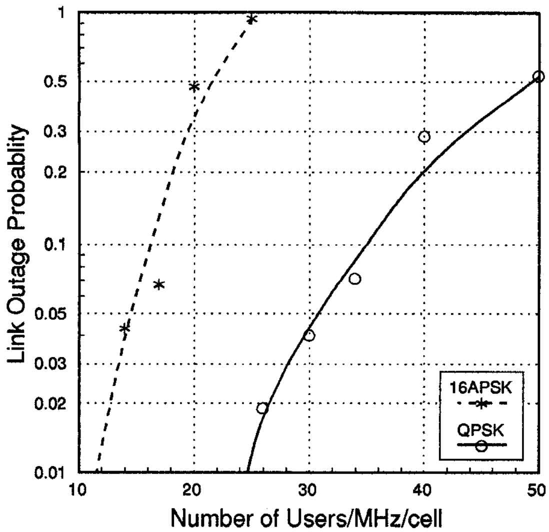

Figure 3: Performance of 16APSK and QPSK.

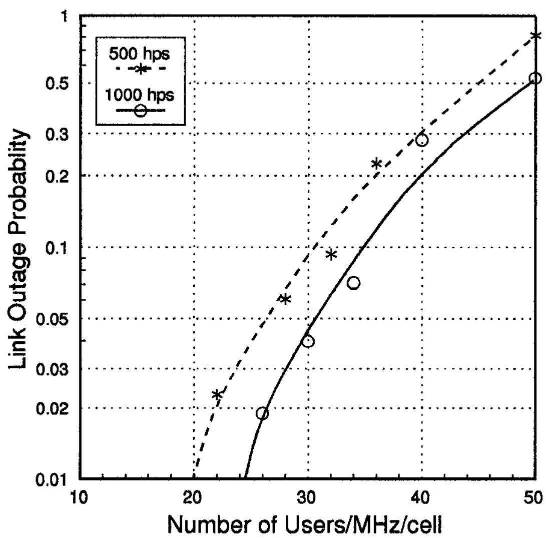

Figure 4: Performance of QPSK with different hop rates.

V. Discussion

The performance of a 16 level linear modulation scheme has been found to be inferior to that of QPSK in the FH cellular environment. Despite offering twice as many hop channels per MHz, thereby reducing the average level of interference, the required C/I protection ratio for 16APSK is so high that its performance is severely degraded by even limited interference. Conversely, QPSK is far more resilient to interference, since its phase decision thresholds are greater, and no amplitude decision is necessary.

The effect of an improvement in performance with increasing hop rate are a consequence of the nature of the FH channel. Recent propagation measurements by the authors have indicated that the mean fade duration of the received signal reduces as the rate of hopping increases. Thus the length of error bursts due to fading are reduced, which corresponds to a decrease in the load placed upon the coding scheme.

The performance of the simulated system was found to be highly dependent upon the level of coding complexity, and there is scope for further investigation into the most suitable coding scheme. Analysis of the error statistics at the input to the demodulator reveals the bursty nature of errors propagating through the Viterbi decoder during periods of severe interference. At these times, the de-interleaving process, whilst randomising the errors of any one hit, serves only to *decrease* the separation of independent erroneous bits from different hits. This results in the breakdown of the decoder trellis, with consequential error bursts appearing in the decoded bit stream. The use of a Reed Solomon block error correcting code overlaid onto the convolutional code is being considered as a solution to this problem.

The performance of the convolutional code described was found to be far superior to that of a (15,7) BCH code. Whilst the phenomenon of decoder breakdown in the presence of high levels of interference does not occur with the BCH code, its overall error correcting capability is lower in this environment.

The results presented here concur with recent work in suggesting that, in terms of traffic capacity, the FH cellular architecture considered could provide the basis for a viable air interface for future Personal Communication Systems. Also, when compared against a DS-CDMA architecture [18], it has been shown that such a frequency hopping scheme is a competitive alternative in terms of spectrum efficiency. The proposed scheme has not been fully optimised, and there several areas that require further consideration.

Acknowledgements

This work has been partly funded under the U.K. DTI/SERC LINK Personal Communications Program. D.J. Purle is funded by a U.K. SERC CASE Award with GPT Beeston.

References

1. *"Report of the Fourth Meeting of ad-hoc UMTS"*, UMTS Doc(91) 14, ETSI/RES/ad-hoc/UMTS, Paris, April 1991.
2. D.C. Cox, *"Wireless Network Access for Personal Communications"*, IEEE Communications Magazine, Vol.30, No.12, Dec. 1992.
3. *"Race Mobile Telecommunications Workshop"*, Metz, France, June 1993.
4. *"An Overview of the Application of CDMA to Digital Cellular Systems and Personal Cellular Networks"*, Qualcomm Inc., Doc. No. EX60-10010, May 1992.
5. J.K. Omura, *"Spread Spectrum Radios for Personal Communication Services"*, IEEE 2nd International Symposium on Spread Spectrum Techniques & Applications, ISSSTA'92, Yokohama, Japan, 1992.
6. D.L. Schilling, *"Broadband Spread Spectrum Multiple Access for Personal and Cellular Communications"*, 43rd IEEE Vehicular

Technology Conference, New Jersey, USA, May 1993, pp.819-822.

7. M. Ewerbring, B. Gudmundson, P. Teder & P. Willars, *"CDMA-IC: A Proposal for Future High Capacity Digital Cellular Systems"*, 43rd IEEE Vehicular Technology Conference, New Jersey, USA, May 1993, pp.440-443.
8. G.R. Cooper & R.W. Nettleton, *"A Spread-Spectrum Technique for High-Capacity Mobile Communications"*, IEEE Transactions on Vehicular Technology, Vol.VT-27, No.4, Feb. 1978, pp.264-275.
9. D.J. Goodman, P.S. Henry & V.K. Prabhu, *"Frequency-Hopped Multilevel FSK for Mobile Radio"*, The Bell System Technical Journal, Vol.59, No.7, Sept. 1980, pp.1257-1275.
10. N. Livneh, R. Meidan, M. Ritz & G. Silberschatz, *"Frequency Hopping CDMA for Future Cellular Radio"*, 42nd IEEE Vehicular Technology Conference, Denver, USA, May 1992, pp.400-404.
11. J.W. Ketchum & M.S. Wallace, *"Reed-Solomon Coding and Slow Frequency Hopping for Narrowband Digital Cellular Systems"*, 42nd IEEE Vehicular Technology Conference, Denver, USA, May 1992, pp.225-228.
12. T. Busby, *"Hardware Considerations for a FH-CDMA Handset (WP2200) & for a FH-CDMA Base-Station (WP2300)"*, U.K. LINK CDMA Project, Doc: LINK/CDMA/BS/01/WP2200-2300/12/92, Draft 1.2, Dec. 1992.
13. GEC -Plessey Semiconductors, *"NJ88C50 Frequency Synthesizer Specification"*, Draft Specification, October 1992.
14. K. Mason, *"Designer Guide to Frequency Synthesis using the UMA1005"*, Philips Semiconductors, Product Concept and Application Laboratory, Southampton, UK, Report No. SCO/AN92002, November 1992.
15. Y.C. Chow, A.R. Nix & J.P. McGeehan, *"Analysis of 16APSK Modulation in AWGN and Rayleigh Fading Channel"*, Electronic Letters, Vol.28, No.17, 13th Aug. 1992, pp.1608-1609.
16. D.J. Purle, A.R. Nix, M.A. Beach & J.P. McGeehan, *"A Preliminary Performance Evaluation of a Linear Frequency Hopped Modem"*, 42nd IEEE Vehicular Technology Conference, Denver, USA, May 1992, pp.120-124.
17. D.J. Purle, S.C. Swales & M.A. Beach, *"Propagation Characteristics of a Frequency Hopped Channel"*, IEE International Conference on Antennas & Propagation, ICAP'93, University of Edinburgh, April 1993, pp.?.
18. S.C. Swales, T. Busby, D.J. Purle, M.A. Beach & J.P. McGeehan, *"A Comparison of CDMA Techniques for Third Generation Mobile Radio Systems"*, 43rd IEEE Vehicular Technology Conference, New Jersey, USA, May 1993, pp.424-427.